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AN EXPERIMENTAL METHOD OF DETERMINING BALLISTIC WINDS MAKING DIRECT USE OF SIRS RADIANCES

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ABSTRACT:

A technique for calculating ballistic winds from satellite infrared spectrophotometer (SIRS) radiance data has been tested. The experiments with SIRS data from both NIMBUS III and IV show the technique has considerable skill in computing ballistic winds.

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ABSTRACT

A proposed ballistic wind determination technique using the satellite infrared spectrophotometer (SIRS) data from NIMBUS III and IV was tested. The general approach was to derive regression equations from a dependent data sample of nearly coincident subsatellite points and rawinsonde locations. The validity of the equations was checked with a smaller independent sample of SIRS radiances from a later period. Tests with the ballistic wind component normal to the path of the NIMBUS III suggested standard errors of less than 10 kts can be achieved. Both zonal and meridional components can be calculated from SIRS-B radiance data which is grouped in clusters. Because the geostrophic ballistic wind is proportional to a horizontal gradient, several techniques were attempted for calculating the gradient at the central point of the irregularly spaced set of data. With proper data handling and adequate spacing of the SIRS-B soundings, the accuracy of the ballistic wind calculations should also be near 10 kts.

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I. INTRODUCTION

In an earlier report, Elsberry and Martin (1971) tested the feasibility of using cloud-corrected radiance measurements from the satellite infrared spectrometer (SIRS) instrument onboard NIMBUS III to directly calculate the ballistic density. The basis for the statistical technique was suggested by K. W. Ruggles CDR (USN) who also proposed that ballistic wind components could be calculated from the SIRS radiances in regions in which the geostrophic assumption is applicable.

The ballistic wind is the weighted integral of the wind encountered at the various levels of the atmosphere through which the projectile travels, that is:

$$\mathbb{V}_B = \frac{1}{\ln p_o} \int_o^{p_o} \mathbb{V}'(\ln p) \; W_v \; (\ln p) \; d(\ln p) \tag{1}$$

where $\mathbb{V}_B$ is the ballistic wind through the depth of atmosphere with surface pressure p_o, and $\mathbb{V}$ and W_v are the actual wind and ballistic wind weighting factor at a pressure level p. In general W_v is proportional to the percent of the time a re-entry vehicle remains in that layer (Finke 1969). Present methods of evaluating the ballistic wind involve the use of rawinsonde and rocketsonde data for the levels in the integration of Eq. (1). Description of the proposed ballistic wind determination technique from satellite measurements is given in the following section (see also Appendix A of Elsberry and Martin).

Wright (1971) has tested three different schemes for calculating ballistic winds from SIRS radiances from both NIMBUS III and IV. The general approach was to derive regression equations from a dependent data sample of nearly coincident subsatellite points and rawinsonde locations. Then the validity of the equations was checked with a smaller independent sample of SIRS radiances from a later period. Wright's results for the SIRS-A experiment (NIMBUS III) and SIRS-B experiment (NIMBUS IV) are summarized in Sections III and IV. In the last section some techniques to improve the ballistic wind determination from the irregularly-spaced SIRS-B locations are examined.

II. DEVELOPMENT OF EQUATIONS

A. FEASIBILITY OF THE USE OF SIRS DATA

If the geostrophic approximation is assumed, Eq. (1) can be expressed as:

$$\mathbb{V}_B = \frac{1}{\ln p_0} \int_0^{p_0} -\frac{g}{f} \, 1k \times \nabla_p \, Z(x,y,\ln p) W_v(\ln p) d(\ln p) \qquad (2)$$

or, rearranging terms:

$$\mathbb{V}_B = \frac{-g}{f \ln p_0} \, 1k \times \nabla_p \int_0^{p_0} Z(x,y,\ln p) W_v(\ln p) d(\ln p) \qquad (3)$$

where g is the acceleration due to gravity, f is the Coriolis parameter, and $\nabla_p Z$ is the horizontal gradient of geopotential height on a constant pressure surface. Expressing the weighting function W_v as a linear combination of known arbitrary functions of ln p, say F_i (ln p), we may write

$$W_v(\ln p) = \sum_{i=1}^{n} a_i F_i(\ln p) \qquad (4)$$

where a_i are constants. Similarly, Z(x, y, ln p) can be expressed as

$$Z(x, y, \ln p) = \sum_{i=1}^{n} r_i H_i(s, y, \ln p) \qquad (5)$$

where r_i are the constants and H_i are a set of arbitrary functions of ln p. Substitution of Eq. (4) and Eq. (5) into Eq. (3) produces

$$\mathbb{V}_B = \frac{-g}{f \ln p_o} \, \mathbb{k} \times \nabla_p \sum_{i=1}^{n} a_i r_i \int_o^{p_o} H_i(x,y,\ln p) F_i(\ln p) d(\ln p) \tag{6}$$

Now consider the radiative transfer equation for the radiance I_i observed by the i^{th} channel of the SIRS, sensing at wave number ν_i.

$$I_i = I_{oi}\left[A, \nu, T(\ln p), \tau(\nu, \ln p)\right] + \int_{p_o}^{o} B_i\left[\nu, T(\ln p)\right] \frac{d\,\tau\,(\nu, \ln p)}{d(\ln p)} \, d(\ln p) \tag{7}$$

Here I_{oi} is the radiance emitted by a contaminant such as the top surface of clouds expressed as a function of A (amount of cloud cover), ν, and T(ln p), the temperature structure above the clouds. The Planck radiance at wave number ν and temperature T is represented by $B_i\left[\nu, T(\ln p)\right]$, and $\tau(\nu, \ln p)$ is the fractional transmittance of the atmosphere at wave number ν from pressure level p to the SIRS. Smith et al (1970) have shown that the cloud contaminant term can be evaluated by an iterative procedure. With that term evaluated, Eq. (7) becomes

$$N_i = \int_{p_o}^{o} B_i\left[\nu, T(\ln p)\right] \frac{d\,\tau\,(\nu, \ln p)}{d\,(\ln p)} \, d(\ln p) \tag{8}$$

where N_i is the radiance corrected for cloud contamination effects, also called the clear-column radiance. Since the only constraints on F_i are that they are known functions of ln p, we specify

$$F_i = \frac{d\,\tau\,(\nu, \ln p)}{d \ln p}$$

because the envelope of the functions F_i has the same shape as the ballistic weight factors. Similarly, since $B_i\left[\nu, T(\ln p)\right]$ is an increasing function of T (lnp) and satisfies the constraints put on H_i in Eq. (5) and we can set:

$$H_i = B_i \left[\nu , T (\ln p) \right]$$

Substituting these expressions into Eq. (8) yields

$$N_i = \int_{p_\infty}^{o} H_i F_i \, d(\ln p) \tag{9}$$

Using this in Eq. (6) results in a direct expression for ballistic winds in terms of the SIRS radiances

$$\mathbb{V}_B = - \frac{g}{f \ln p_\infty} \mathrm{l}k \times \nabla_p \sum_{i=1}^{n} a_i r_i N_i \tag{10}$$

where n is the number of SIRS channels used. In practice, the coefficients $a_i r_i$ are grouped together and are statistically determined through the use of the BIMED 02R stepwise multiple regression routine (Dixon, 1966). This produces a final equation of the form

$$\mathbb{V}_B = - \frac{1}{f} \mathrm{l}k \times \nabla_p \left[\sum_{i=1}^{n} b_i N_i + C_1 \right] \tag{11}$$

where b_i are the regression coefficients and C_1 is the regression equation constant. The constant terms g and $\ln p_\infty$ are absorbed by the coefficients, b_i.

B. BALLISTIC D VALUE APPROACH

The geostrophic assumption is explicit in Eq. (11), and we may interpret the term within brackets as a geopotential. Ballistic wind weighting factors applied to the height deviations (D values) from standard geopotential heights were used in calculating the bracketed term, which we call the ballistic D value. This method of calculating $\mathbb{V}_B$ then consisted of two steps. First a regression equation for the D value was calculated from a dependent sample of rawinsonde-derived D values and SIRS radiances. All available data at mandatory reporting levels between the surface and 10 mb were used in calculating the ballistic D values from rawinsonde observations, (see Elsberry and Martin 1971 for discussion of the application of the ballistic weighting factors for layers between mandatory levels from the values given by Finke 1969). Above the termination level of the sounding the temperature values were extrapolated to 1 mb using the standard January lapse rate at 45 N, and the hydrostatic equation was used to complete the D value profile. The second step was to use Eq. (11) with the derived regression equation to calculate the ballistic wind.

C. GRADIENT OF RADIANCES APPROACH

Rearrangement of the order of Eq. (11) yields

$$\mathbb{V}_B = -\frac{1}{f}\left[\sum_{i=1}^{n} c_i \;(\mathbb{1}k \times \nabla_H N_i) + C_2\right] \tag{12}$$

Although mathematically equivalent, the procedure for evaluation of Eq. (12) is different than the previous approach. In this case the regression equation was derived by correlation of values of $\mathbb{V}_B$ with gradients of the individual radiances N_i as shown within the parentheses. Thus the regression coefficients c_i and the constant C_2 are not equivalent to b_i and C_1 in Eq. (11). A dependent sample relating the observed east-west component (u_B) and north-south component (v_B) was obtained from Eq. (1) using rawinsonde observations with nearly coincident SIRS radiances. Missing interior mandatory level winds were linearly interpolated. Completion of the sounding to 1 mb was by extrapolating parallel to a mean zonal wind profile for that component and by decreasing the v component by five percent with each mandatory level increment. Since soundings were not processed unless data was present to at least 100 mb, the reduction toward zero for the v component is probably justifiable.

III. SIRS-A EXPERIMENT

A. DATA AND DATA HANDLING

The data used in this experiment were from the same set used by Elsberry and Martin (1971). Radiances, corrected for cloud contamination, were available for the eight SIRS channels during two four-day periods: December 27-30, 1969, and January 2-5, 1970. The area of data coverage was the European continent including the area of the U.S.S.R. west of the Urals, and the time period covered was from 0800 GMT to 1200 GMT for each day. The dependent ballistic D values and ballistic winds were computed from the 1200 GMT rawinsonde data from the same periods. The rawinsonde data did not include any data from France or the British Isles. In some cases this was a limitation due to the location of satellite subtracks lying in this data sparse zone. In addition, data was typically quite sparse in the Mediterranean region.

The 27 degree longitudinal spacing of NIMBUS III SIRS-A data precludes the calculation of both u and v components of ballistic winds by the geostrophic approximation. Instead, V_{BN}, the wind component normal to the satellite subtrack was calculated using Eqs. (11) and (12) modified as indicated below

$$V_{BN} = -\frac{g}{f}\frac{\partial}{\partial n}\left[\sum_{i=1}^{n} b_i N_i + C_1\right] \tag{11a}$$

$$v_{BN} = -\frac{1}{f}\left[\sum_{i=1}^{n} d_i \frac{\partial Ni}{\partial n} + C_2\right] \quad (12a)$$

Here n is the generally northerly direction parallel to the satellite subtrack. A typical NIMBUS III subtrack and data are shown in Fig. 1. .

The ballistic D values and values of u_B and v_B calculated from all available rawinsonde data were plotted and each of the fields analysed by hand. Values were then interpolated to SIRS subtrack positions. Since the points with SIRS data were irregularly spaced, a cubic spline fitting interpolation routine was used to obtain radiance data at 120 n. mi intervals along the satellite subtrack. Although this interpolation produced a smoothing of the radiance values, Wright (1971) has shown that the standard error of estimating the ballistic D value was changed by less than two meters (about four percent).

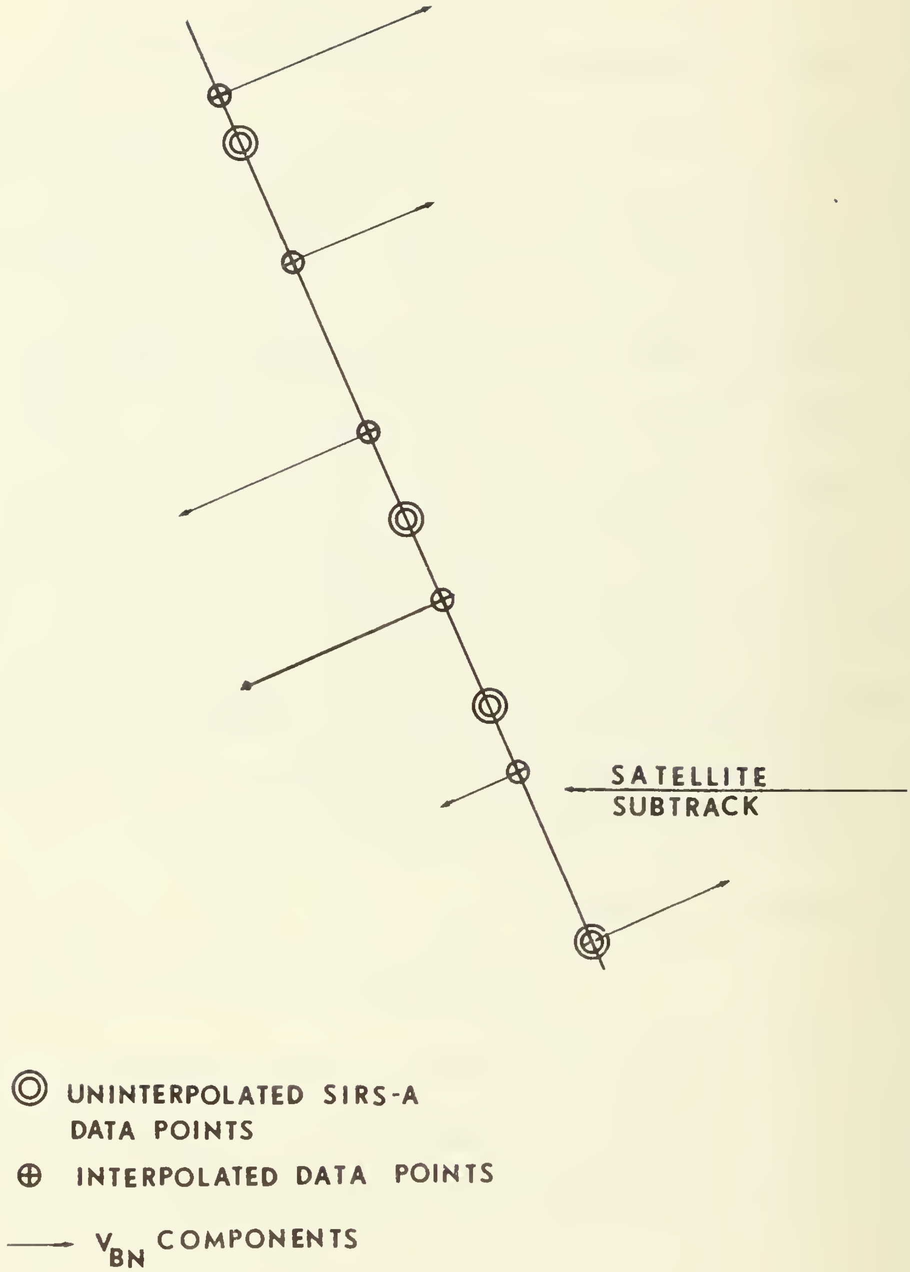

Fig. 1. Typical Nimbus III Satellite Subtrack Showing Uninterpolated and Interpolated SIRS-A Data.

B. BALLISTIC D VALUE APPROACH

Correlation of the ballistic D values and the eight cloud-corrected SIRS radiances led to the regression equation

$$D_B = 1.281\ N_1 - 5.243\ N_2 + 13.642\ N_3 + 7.884\ N_4 - 58.512\ N_5$$

$$+ 63.779\ N_6 + 9.836\ N_7 - 1.088\ N_8 - 1822.8 \qquad (13)$$

for the dependent December data. For the January data the corresponding equation was

$$D_B = -5.497\ N_1 - 58.457\ N_2 - 42.484\ N_3 + 32.944\ N_4 - 91.296\ N_5$$

$$+ 40.878\ N_6 - 10.980\ N_7 + 14.980\ N_8 + 1792.3 \qquad (14)$$

Channels 2 through 6 contributed significantly to the D_B in the January sample, while the leading terms for the December sample involved only channels 5 and 6. This suggests rather poor temporal stability and the need for sequential updating of the dependent sample. As discussed by Elsberry and Martin (1971), the earlier period was marked by a stratospheric warming with a generally anomalous tropospheric flow pattern as well. All the ballistic winds were westerly in the January independent sample (Table 1) so that the mean V_{BN} was equal to the mean of $|V_{BN}|$. The December 30 sample contained both easterlies and westerlies with an average magnitude of the ballistic wind of about 24 kts. As a result the standard deviation of the December sample was almost 30 kts compared to a value of about 10 knots in the more uniform January sample.

Estimates of V_{BN} from gradients of the D values calculated with Eqs.

TABLE 1

Comparison of Ballistic Winds Derived from Rawinsondes and from Regression Equations Using SIRS-A Radiances

Approach	η	Mean V_{BN}	Std Dev V_{BN}	Mean $\lvert V_{BN} \rvert$	Corr Coeff	Explained Variance	Std Error	Max Error
				DECEMBER 30				
D Value	23	4.7 Kts	29.1	24.2	.896	80.3%	13.3 Kts	39.6
Gradient N	27	6.6 Kts	28.5	23.9	.956	91.4%	8.5 Kts	24.1
				JANUARY 5				
D Value	11	40.0 Kts	8.2	40.0	.822	67.5	4.9 Kts	9.3
Gradient N	19	37.1 Kts	13.1	37.1	.626	39.1	10.5 Kts	24.1

(13) and (14) using SIRS-A radiances for the two independent samples are also shown in Table 1. The ballistic wind explained variance for this D value approach ranged from 80 percent for the December sample to 67 percent for the January sample. It is somewhat surprising that the standard error of the latter sample was only 5 kts. considering the magnitude of the ballistic winds. Such errors are close to the present rawinsonde errors in high wind regions. Extrapolation of rawinsonde winds to higher levels for integration of the ballistic wind equation can also introduce errors of this size.

C. GRADIENT OF N_i APPROACH

The derivatives $X_i \equiv \frac{1}{f} \frac{\partial N_i}{\partial n}$ along the satellite subtrack were correlated with the observed values of the normal ballistic wind components V_{BN}. For the December dependent data the resulting regression equation was

$$V_{BN} = -2.371\ X_1 - 11.456\ X_2 + 30.703\ X_3 - 1.548\ X_4 + 64.865\ X_5$$
$$- 25.090\ X_6 - 2.122\ X_7 + 2.251\ X_8 + 24.42$$

Except for the use of the spline fitting technique to derive radiances at equally-spaced latitude points in the gradient calculation, this approach was quite direct. As a result of differences in data-handling, the sample size varied slightly for this method compared to the D value approach.

Estimates of the ballistic winds with the gradient of N_i approach (also summarized in Table 1) varied considerably for the two independent samples. Over 90 percent of the variance was explained with a standard error of about eight kts for the December sample. Much less skill was shown for the results in January since only about 40 percent of the variance was explained. Even though the standard error for January 5 was only about 10 kts, this is relatively large compared to the standard deviation of the sample. Evidently the larger number of derivatives required for the gradient of N_i approach introduces a variability in the results with this method. Wright (1971) has tested this method without interpolating the radiances. In both the gradient of N_i and the ballistic D value approaches, the use of variable increments caused a considerable reduction in explained variance and an increase in the standard error. Inherent smoothing by the interpolation scheme seems to reduce the scatter in the radiance data introduced by the independent calculations of cloud correction at adjacent subsatellite scanspots.

IV. SIRS-B EXPERIMENT

A. DATA AND DATA HANDLING

The SIRS-B instrument carried onboard NIMBUS IV was noteworthy for its side-viewing capability. It was thus anticipated that a more uniform distribution of radiance data would be available to permit the calculation of both horizontal components of the ballistic wind. A 30-day period in late December 1970 and January 1971 was chosen, as the high winds during this period would provide a good test of the ballistic wind regression scheme. Unfortunately the window channel was inoperative during this period so only the seven carbon dioxide channels were available.

As was the case in the previous experiments, concurrent rawinsonde data and corrected clear column radiances from SIRS-B were required. To permit calculation of gradients, the data were chosen from areas where several SIRS data points could be grouped into a cluster. These clusters consisted of one master data point surrounded by three to six other "slave" points, as shown in Fig. 2. In areas with SIRS-B coverage the normal spacing between data points was 450 to 650 km. The maximum difference between a master and a slave was arbitrarily limited to 1000 km. As only the archived NESS clear-column radiances were available, the data coverage was generally poor. Data were restricted to the latitude belt 40N to 75N. An eight-day period was used to collect enough data to derive and test regression equations analogous to those in the SIRS-A experiment. A total of 45 separate data clusters comprising 194 points were found in the period 10-17 January 1971. The first 30 clusters occurring from 10-14

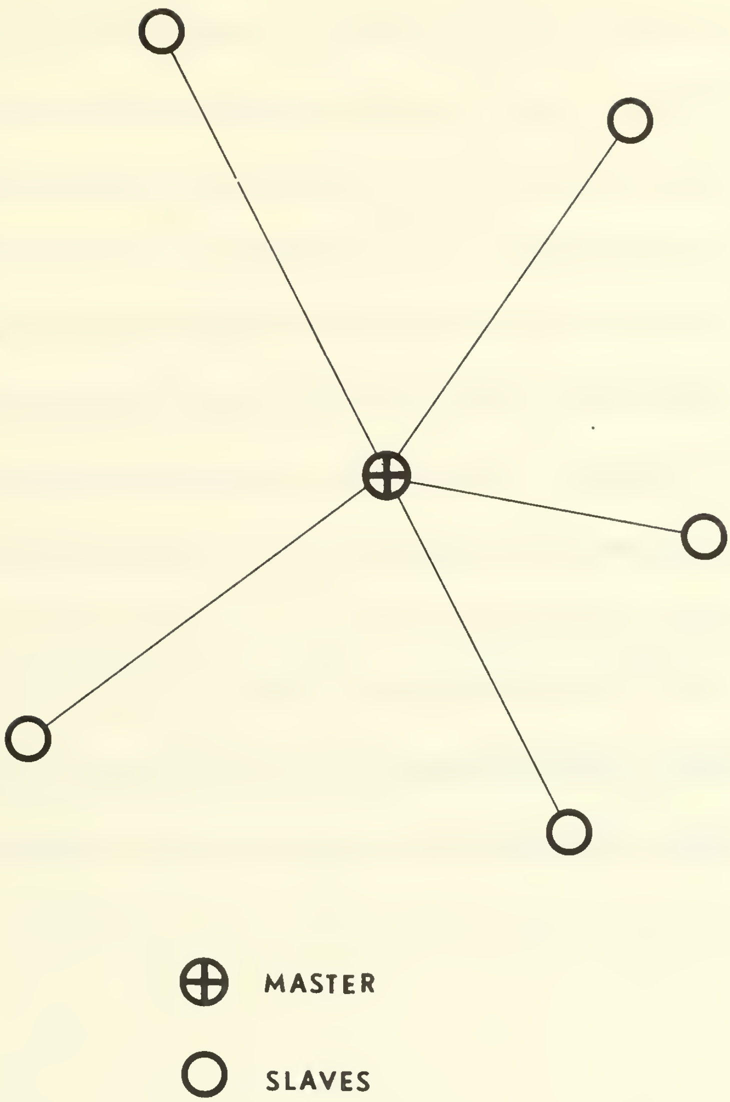

Fig. 2 Sample SIRS-B Data Cluster

January were used as the dependent sample, and the remaining 15 formed the independent sample.

Calculation of both the east-west (u) and north-south (v) components of Eqs. (11) and (12) was possible with the SIRS-B data clusters. In Eq. (11) the gradient of the ballistic D value was required at the master point, while a total of seven gradients of the radiances in the cluster was necessary in Eq. (12). Wright (1971) assumed the surface between each master-slave pair was linear and a plane was fitted through the data of each pair. The slope of each plane was converted to an east-west and north-south gradient, and the average of such gradients for all master-slave pairs (between three and six pairs) was taken to be the partial derivative of the D (or N_i) value. With this technique the required partial derivatives could be rapidly calculated. We will discuss in a later section other methods for determining the D value gradient at the center of an irregularly-spaced data cluster.

B. BALLISTIC D VALUE APPROACH

Ballistic D values were calculated using radiosonde temperatures from stations in the region of each data cluster and then interpolated to the location of each subsatellite point in the cluster. Soundings were extrapolated only to 1 mb, rather than to the 0.07 mb level used in the SIRS-A study. The contribution to the D value in the layer between these two levels was generally small, and always based on extrapolated data following the January standard atmosphere lapse rate.

Correlation of rawinsonde-derived D values with the radiance data for all 130 data points in the dependent sample produced the relation

$$D_B = -10.82\ N_2 + 15.23\ N_4\ -47.41\ N_6 + 95.96\ N_7 - 30.45\ N_8 - 1727.6 \tag{15}$$

This equation which is analogous to Eqs. (13) and (14) explained only 81 percent of the variance of D_B in the dependent sample with a standard error of 120 meters. The large standard error was probably due to the long time period, as well as to large variations in latitude and longitude. It should also be noted that the window channel was missing during this period and only five of the remaining seven channels gave statistically significant contributions.

Radiances from the 15 clusters in the independent sample were used in the above regression equation and gradients of the D value were calculated at the master point using Wright's technique. These SIRS-B derived wind components were correlated with the rawinsonde ballistic winds drawn from the analysis at the same point. The mean west wind component (see Table 2) of 21 kts has a standard deviation of 19 kts. Again the mean of the absolute value of this component shows most of the winds were westerly. Although the mean north-south component was near zero, the standard deviation of v_B was about 15 kts. In the D value approach the correlation coefficient for the north-south component was just slightly less than that obtained in the SIRS-A results for the normal component. The standard error of the estimate of 9.5 kts also compares favorably. However the estimate using the D value approach explains only 27.6 percent of the variance of the zonal component. A standard error of 17 knots also appears excessive. Some of this error is due to the oversimplification of Wright's technique for evaluating the gradient from the irregularly spaced array. In addition the distances involved in the gradient calculation were large compared to the rather closely-spaced SIRS-A data. The larger standard error of the D value estimate from Eq. (15) also plays a role.

TABLE 2

Comparison of Rawinsonde-derived and Regression-derived
Ballistic Winds Using SIRS-B Radiances

Approach	η	Mean u/v	Std Dev	Mean $\lvert u\rvert, \lvert v\rvert$	Corr Coeff	Explained Variance	Std Error	Max Error
EAST-WEST COMPONENT								
D Value	15	21 Kts	19 Kts	24 Kts	.525	27.6%	17 Kts	32 Kts
Gradient N					.529	28.0%	17 Kts	32 Kts
NORTH-SOUTH COMPONENT								
D Value	15	-2.5 Kts	15 Kts	14 Kts	.807	65.2%	9.5 Kts	18 Kts
Gradient N					.722	52.1%	11 Kts	29 Kts

C. GRADIENT OF N_i APPROACH

As shown in Eq. (12) the u and v components of the ballistic wind may be correlated with the N_i gradients evaluated at the master point of each cluster, i. e., with

$$X_i \equiv -\frac{1}{f} \quad \frac{\partial Ni}{\partial y} \qquad \text{and} \qquad Y_i \equiv \frac{1}{f} \quad \frac{\partial Ni}{\partial x}$$

The inclusion of the Coriolis parameter (f) reflects the normalization of latitude effects in the sample. Using Wright's technique for evaluating the gradients, equations from the dependent sample (n = 30) were

$$u_B = 152.2\, X_2 \;\; -255.8\, X_3 + 344.7\, X_4 + 197.6\, X_6 \;\; -695.7\, X_7$$
$$+ 292.7\, X_8 + 14.74$$

$$v_B = -133.4\, Y_2 \;\; -121.0\, Y_3 + 144.4\, Y_4 -146.0\, Y_6 \;\; + 568.8\, Y_7$$
$$-129.6\, Y_8 \;\; + 5595.$$

Each of the seven channel s contributes to the regression in this method. For the dependent samples these equations explained 54 and 58 percent of the variance in the u and v components. The standard error for each component was 18 kts.

The results for the independent sample of radiances with the above equations are shown in Table 2. Again the east-west component was not estimated as well as the north-south component. In fact the results for the east-west component are nearly the same as for the D value approach.

The gradient of N_i approach gave slightly poorer estimates of the north-south component. It was noted in the SIRS-A section that the gradient of N_i method seems to be consistently less useful because of the many gradients to be calculated. The large distances over which the gradients were evaluated probably contributes to the less favorable results.

As calculation of the gradient appeared to be a major source of error with the SIRS-B data cluster, in the next section we examine some other methods of evaluating the gradient at the master point. These methods are only tested with the ballistic D value approach, which produced superior results in both the SIRS-A and SIRS-B experiments.

D. ALTERNATIVE METHODS OF DETERMINING D VALUE GRADIENTS

The evaluation of the ballistic wind components at the master location, corresponding to a subsatellite point, is dependent on the east and west gradients of the ballistic D values through the geostrophic relation. Various methods can be used to calculate these gradients given the D values at the master and irregularly-spaced slave locations. Wright (1971) used a straight-forward averaging method for calculating the slopes of the D surface at the master point. More general relations for the gradients can be obtained by expressing the set of D values in the region of master point (X_o, Y_o) as

$$D = a_1 + a_2 (x-x_o) + a_3 (y-y_o) + a_4 (x-x_o)(y-y_o) + a_5 (x-x_o)^2 + a_6 (y-y_o)^2 + \ldots \tag{16}$$

Here the coefficient a_1 represents the D value at the master point and the and the gradients of D may be written as

$$\frac{\partial D}{\partial x} = a_2 + a_4 (y-y_o) + 2\, a_5 (x-x_o) + \ldots$$

$$\frac{\partial D}{\partial y} = a_3 + a_4 (x-x_o) + 2\, a_6 (y-y_o) + \ldots \tag{17}$$

At the master point only the coefficients a_2 and a_3 contribute, but their values will change depending on the number of terms which are included in the expansion. At the minimum, there must be one master-slave pair for each additional coefficient added in the expansion. Thus to determine a_2 and a_3 requires at least three master-slave pairs. If more than this number of pairs is available, the coefficients may be obtained by a statistical regression which best fits (in a least-square sense) the values of D at all the available points in a cluster.

The multiple regression package BIMEDO3R of Dixon (1966) was used to obtain the coefficients a_2 and a_3 with three degrees of approximations in Eq. (16) for the D surface: (1) a linear regression equation including only the first three terms, (2) with the addition of one second order term, $a_4(x-x_o)(y-y_o)$, and (3) with the addition of the $a_5(x-x_o)^2$ and $a_6(y-y_o)^2$ terms, but not the a_4 term. All 45 samples used by Wright (1971) could be used with the first (linear) approximation, but only 33 samples contained at least four master-slave pairs and could be used with the second approximation. A more severe reduction in sample size occurred with the third approximation as only nine clusters had at least five master-slave pairs. This reduction in sample size could have been minimized if the space (ten degrees latitude) and time (less than two hours separation) restrictions set by Wright (1971) had been relaxed. Nor is this data sample typical of the distribution which might be expected if the technique discussed here were to be used operationally. It should be emphasized that the clear-column SIRS-B data were processed for a different purpose. Many more data exist on the SIRS-B file, but the selection of data locations and numbers actually processed was made by the National Environmental

Satellite Service for calculating temperature profiles. The necessity for a different processing selection for use with this technique should be obvious.

Since at the master point the coefficients a_2 and a_3 are the desired gradients of D in the x-and y-directions, the geostrophic relation may be introduced as

$$\frac{\partial D}{\partial x} = \frac{fv}{g} \quad \text{and} \quad \frac{\partial D}{\partial y} = -\frac{fu}{g}$$

where g is the gravitational acceleration and f is the Coriolis parameter at the master location. Both g and f are constants for a given master-slave cluster and thus may be absorbed in the regression constant. It might also be noted that the correction for longitudinal increment Δx was important since the data sample was from a belt between 40 N and 75 N.

Several sources of error may be distinguished for this method. The calculation of the D values from Eq. (15) using the satellite radiances introduces some scatter in the adjacent values. This may especially occur if very different corrections to the observed radiances are introduced due to different cloud cover. Although rather large standard errors for the D values were found by Wright (1971), often the majority of the points in a cluster would have the same sign and magnitude, which does not affect the gradient. Some particular examples were noted near the centers of deep lows, where the minimum D values were underestimated but the high wind speeds were correctly calculated. A second error occurs in using Eq. (16) to fit a surface to the irregularly spaced data. In a few cases a very accurate representation of the D values calculated from the radiances was achieved, but the corresponding slopes of this surface did not match the observed wind components at master point. For this reason an optimum surface fitting technique should also be able to handle D values from Eq. (15) which may be unrepresentative. In an operational system individual clusters should not be treated, but rather an objective analysis scheme should be employed so that the calculation of the D gradients could be made from a regularly spaced grid. Unrepresentative D values would be filtered by the objective analysis with a good first-guess field from the previous analysis and proper gross-error checks. A third source of error occurs because the D value approach is based on assumption of geostrophic wind components. Thus the wind speed will be overestimated in areas of cyclonic curvature since the centripetal acceleration is neglected.

The best test of the contribution from the error in estimating the ballistic D value from the satellite radiances should be to calculate the corresponding geostrophic wind components at the master point using the observed ballistic D values at all the points. Thus if the regression equation (15) for D_B was perfect, and the same method of estimating the gradients were used, the ballistic winds calculated using the satellite radiances would be equal to those using the radiosonde ballistic D values. Because the radiances are from a single instrument, the satellite method may occasionally produce a better estimate of the wind in regions of sparse or inhomogeneous rawinsonde coverage. In the following tables the ballistic wind estimates from both the satellite radiance data and the observed radiosonde data will be compared with the observed ballistic wind components at the master point. As noted above, three degrees of approximation in Eq. (16) will be used in testing the method of calculating the ballistic D value gradients at the master point, which is related to the geostrophic wind component.

The first test (see Table 3) was to determine the ballistic wind components using the linear regression equation approach in Eq. (16). Results for both the dependent (10-14 Jan 1971, $\eta = 30$ samples) and the independent (15-17 Jan 1971, $\eta = 15$ samples) cases are shown. The D values for the latter sample are derived from the clear-column radiances using Eq. (15). Comparison with Wright's slope-averaging approach (shown in parentheses in Table 3) shows that the linear regression approach raises the correlation coefficient and lowers the standard error of the estimate in the cases where these were least satisfactory using the Wright approach. However the reverse is generally true for the instances in which the Wright approach showed the most skill. As the changes are small there appears to be little statistical difference between the two methods.

Table 3. Correlation coefficient and standard error of the estimate for zonal (u) and meridional (v) components of the actual ballistic wind (kts) calculated by a linear regression equation (see text). Corresponding values obtained by a slope-averaging process due to Wright (1971) are shown in parentheses.

		Dependent $\eta = 30$		Independent $\eta = 15$	
Satellite D Values	u	.707 (.661)	16.8 (17.8)	.558 (.525)	16.8 (17.0)
	v	.750 (.775)	16.6 (15.9)	.779 (.807)	10.1 (9.5)
Radiosonde D Values	u	.875 (.860)	11.5 (12.1)	.796 (.812)	12.2 (11.8)
	v	.894 (.875)	11.3 (12.2)	.576 (.431)	13.2 (14.6)

Comparison of the satellite D value approach with that using the radiosonde D values shows the expected decreased accuracy of estimating the wind speeds for all samples except the v components in the independent sample. The difference in accuracy for the u and v components appears to result from a different type of wind regime and the small independent sample. One would expect there would be no preference for wind components (as shown in the dependent sample). The differences between u and v components for the satellite-scan and rawinsonde-derived values certainly implies the independent sample was too small. It should also be noted that use of the independent D value sample from the period 15-17 Jan 1971 was a rather severe test of the temporal stability based on a dependent sample from 10-14 Jan 1971. An operational scheme would generally be updated daily using the most recent three-or four-day period. Finally the larger degradation of the zonal component over that of the meriodional component suggests the importance of solving for D regression equations in latitudinal bands.

The second test (Table 4) in determining the error due to evaluating the gradient over an irregular grid was to include one second order term $(x-x_o)(y-y_o)$ in the regression equation. Values of the regression coefficient and standard error of the estimate of the actual ballistic wind are shown in Table 4 where the values in parentheses are for a homogeneous sample from the linear regression technique. For this small sample rather little change was noted with the inclusion of the additional term.

Only three of the eight comparisons showed lower standard error. It is of interest to note that the apparent improvement over Table 3 in the rawinsonde-derived values for the independent sample is mainly a result of choosing a different sample.

Table 4 Correlation coefficient and standard error of the estimate for zonal (u) and meridional (v) components of the actual ballistic wind (kts) calculated with a regression equation including an xy term. Corresponding values obtained with the linear regression equation as in Table 3 are shown in parentheses.

		Dependent N = 21		Independent N = 12	
Satellite D Values	u	.680 (.628)	16.1 (17.1)	.549 (.588)	18.3 (17.7)
	v	.746 (.762)	17.2 (16.7)	.757 (.772)	9.9 (9.7)
Rawinsonde D Values	u	.868 (.903)	10.9 (9.4)	.888 (.814)	10.1 (12.7)
	v	.882 (.869)	12.1 (12.8)	.700 (.776)	10.9 (9.6)

For the third test the $(x-x_o)(y-y_o)$ term was dropped but two second order terms were substituted. The sample size ($\eta = 9$) in this case is so small that no distinction is made between dependent (4) and independent (5) samples in Table 5. As noted above, the inclusion of the $(x-x_o)$ $(y-y_o)$ term gives mixed results. However including the $(x-x_o)^2$ and $(y-y_o)^2$ terms does lead to marked improvement in each case. Since the sample is homogeneous it cannot be argued that these results merely reflect the additional data available in these nine clusters. More samples would be required to establish the magnitude of this improvement, which is consistent with the better representation of the D surface. This particular sample had a mean zonal wind component of 28.1 kts with a standard deviation about the mean of 22.7 kts. Corresponding values for the meridional wind component were -2.7 kts and 18.3 kts. These standard errors of the estimate of less than 10 kts in Table 5 for the regression with x^2, y^2 term thus show considerable skill.

One auxiliary product of the BIMEDO3R program is the standard error of the regression coefficient, which in this case represents the scatter in the u or v components. That is, this value is an estimate of the error made in not being able to fit the data points with the specified surface (linear, second order, etc.). Large values thus indicate poor confidence in the estimate of u or v component. In the large majority of cases for the sample shown in Table 5, the difference between the actual u and v and the estimated u and v components was smaller than the standard error of the regression coefficient. However it must again be cautioned that the D values may be fitted very accurately by the specified surface and yet not predict the wind components if some of the D values are erroneous. Thus a small standard error of the regression coefficient is of the nature of a necessary but not a sufficient condition.

Table 5 Correlation coefficient and standard error of the estimate for zonal (u) and meridional (v) components of the actual ballistic wind (kts) calculated with three regression equations (see text).

Equation		Linear		XY Term		X^2, Y^2 Term	
Satellite	u	.644	18.6	.647	18.5	.737	16.4
D Values	v	.785	12.1	.762	12.7	.894	8.8
Rawinsonde	u	.890	11.1	.775	15.3	.960	6.8
D Values	v	.645	15.0	.735	13.3	.714	13.7

E. BALLISTIC WINDS USING RAW RADIANCES

Examination of those cases with poor estimates of the ballistic wind, and a recent paper by Hayden (1971), prompted an experiment to determine the effect of the cloud correction to the radiances. In several cases within the independent sample the cloud corrected radiances in the channels sensing the upper troposphere and stratosphere varied sporadically about the cluster mean. As each sounding is processed independently, the cloud correction could represent a major portion of the gradient between adjacent soundings. Hayden (1971) compared SIRS-derived soundings with nearby radionsondes. He showed the quality of the temperature profiles from the SIRS-A instrument was degraded after the loss of the 714 cm^{-1} CO_2 channel, which suggested a similar degradation could have occurred with the loss of the window channel. This condition may have been one factor in the less accurate ballistic winds obtained with the SIRS-B radiances. Unfortunately SIRS-B data with the window channel radiances were not available to directly evaluate the effect of the loss of the window channel.

A limited experiment with the D value approach was used to check the effect of the cloud correction in the SIRS-B data sample. A new regression equation was calculated relating the D values to the raw radiances. As is shown in Table 6, the explained variance in the dependent sample was 0.769 versus 0.812 for the cloud-corrected radiances. A larger standard error of the estimate was also obtained for the raw

Table 6. Ballistic parameters calculated using raw SIRS-B radiances versus clear-column radiances (shown in parenthesis).

D VALUE CALCULATION

Sample	Sample Size	Mean D	Std Dev	Correlation Coefficient	Explained Variance	Std Error
Dependent	145	-366.2	268.2	.877	.769	131.7
	(130)	(-345.5)	(269.8)	(.901)	(.812)	(119.2)
Independent	78	-330.4	165.8	.765	.585	107.5

BALLISTIC WIND - LINEAR REGRESSION

	Dependent $\eta = 30$		Independent $\eta = 15$	
Component	Correlation Coefficient	Std Error	Correlation Coefficient	Std Error
u	.684	17.4	.600	16.2
	(.707)	(16.8)	(.558)	(16.8)
v	.535	21.3	.631	12.53
	(.750)	(16.6)	(.779)	(10.1)

radiances. The test with the independent sample resulted in a reduced standard error, but the sample standard deviations were also reduced.

For our purposes the comparison of the derived wind components is the more important criterion. The first order linear regression equation approach discussed in the previous section was used to calculate the D value gradient, and thus the derived ballistic wind components. Values in parentheses in Table 6 were abstracted from Table 3 for comparison with the raw-radiance winds. Although the differences in the correlation coefficient and the standard error were rather small for the u component in the dependent sample, those for the v component were much worse. The v component results were also degraded in the independent sample, while the u component results were actually improved. It is clear that use of the cloud-corrected radiances is important for the v component. Not much conclusive can be stated for such a small sample, but the results suggest that some of the reduced accuracy in the u component versus the v component may be due to the cloud correction.

V. CONCLUSIONS

The objective of this research was to demonstrate the feasibility of calculating ballistic winds using SIRS radiances, and to explore the different approaches for calculating the ballistic wind. Ruggles (see section II) has suggested the mathematical basis for a direct calculation of the ballistic winds by evaluating gradients of radiances sensed by the SIRS instrument. In a second approach the D value (deviation from the standard height) times the ballistic wind weighting factor was integrated through a deep layer of the atmosphere, and the geostrophic ballistic wind was calculated from the gradients of these ballistic D values.

Only components normal to the path of the NIMBUS III satellite could be calculated in the SIRS-A experiment. A spline-fitting routine was used to interpolate the large number of irregularly spaced "soundings" to equal increments along the track. Statistical regression between the ballistic wind and the gradients of the D values, or of the radiances, showed very good temporal stability when tested against the independent sample of 30 December 1969 (see Table 1). Although the regression equations with the second, smaller independent sample on 5 January 1970 were not as stable, the test suggests standard errors of less than 10 kts could be achieved.

Both ballistic wind components can be calculated from the "side-looking" SIRS-B instrument, but the method of calculating the gradient required clusters of SIRS scan points. The clusters of irregular, widely-spaced subsatellite points required more data handling and restricted the sample size. A larger standard error of estimate (see Table 2) resulted with the SIRS-B data, particularly when the east-west component of the wind was calculated. Fitting higher order approximations to the D values led to improved estimates of the wind components at the central point. With proper data handling and adequate spacing of the processed soundings, it would appear that the accuracy should be comparable to that for the SIRS-A instrument.

The use of SIRS radiances for deriving temperature profiles over a deep layer of the atmosphere has been demonstrated by Smith et al (1970) and Hayden (1971). In an earlier report Elsberry and Martin (1971) showed that the ballistic density for a deep layer of the atmosphere could be calculated directly from the SIRS radiances. The capability for viewing a deep layer of the atmosphere is the basis of the success in directly calculating the ballistic wind. Because the wind depends on gradients of the integrated density, the errors in the wind components are proportionately higher. Nevertheless the proposed technique for determining ballistic winds shows considerable promise, especially for the oceanic or other data-void regions.

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13. ABSTRACT

A proposed ballistic wind determination technique using the satellite infrared spectrophotometer (SIRS) data from NIMBUS III and IV was tested. The general approach was to derive regression equations from a dependent data sample of nearly coincident subsatellite points and rawinsonde locations. The validity of the equations was checked with a smaller independent sample of SIRS radiances from a later period. Tests with the ballistic wind component normal to the path of the NIMBUS III suggested standard errors of less than 10 kts can be achieved. Both zonal and meridional components can be calculated from SIRS-B radiance data which is grouped in clusters. Because the geostrophic ballistic wind is proportional to a horizontal gradient, several techniques were attempted for calculating the gradient at the central point of the irregularly spaced set of data. With proper data handling and adequate spacing of the SIRS-B soundings, the accuracy of the ballistic wind calculations should also be near 10 kts.

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